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# FLIGHT INSPECTION OF THE SECONDARY SURVEILLANCE RADAR SIGNAL-IN-SPACE


## ABSTRACT

The effectivness of the SSR as a main backbone of ATC is affected by the accumulation of signals in space due to civil, military and also illegal transmissions on both SSR uplink and downlink channel. Conventional methods to inspect the performance of SSR as introduced in DOC8071 are not qualified to identify the real contents within the bandwidth of those channels in case of serious problems.

In contrast to this a proper investigation of the SSR should include a view to the basic incoming pulse shape of telegrams aboard the inspecting aircraft. An experimental system to record the actual SSR Signal-in-Space and some algorithms to analyse the contents are introduced in this paper as well as various measurements done with it during test flights: Heavily overcrowded air spaces induce a high radio load triggered by SSR ground stations and ACAS initiated transponder responses. The results derived from the analyzed SSR video data allow a detailed separation of the involved telegram formats (Mode 1,2,3/A,C,S) so the system's main benefit to be focussed on is the numerical evaluation over time and motion. Further potential included is to detect interference apart from regular SSR telegram transmissions which block transponders or prevent receivers from getting a valid aircraft response.


## INTRODUCTION

Already during World War II U.S. and British Allied Forces developped so-called IFF (*Identification Friend or Foe*) techniques which led to the first releseas of those systems. Developments continued after the war ended and in the meanwhile also civil aviation realized the benefit of active identification of aircraft so the ICAO decided in 1954 to establish a civil derivative in compability to the military variant IFF "Mk X" [7]. It mainly bases on a airborne transponder being interrogated on the uplink channel 1030 MHz and responding on the downlink channel 1090 MHz.

The steady growth of air traffic in the past decades in contrast to fixed frequency resources evokes the question in what way the high radio load on both channels diminishes air traffic control capabilities. The wide-area introduction of the newer, selective SSR variant *Mode S* would contribute to a strong reduction of the radio load: Its main advantage against the conventional Modes 1,2,3/A,C is the capability to transmit selective calls to prevent the majority of airborne transponders from responding. However, for a still unknown period the conventional modes must be maintained because not yet all aircraft are equipped with a Mode S transponder. Furthermore, european countries have currently no operable Mode S ground stations. In Germany i.e., there exists just one experimental interrogator in Götzenhain near Frankfurt whose Mode S extensions are switched off most of the time.

Before the introduction of the Mode S based *Airborne Collision Avoiding System* (ACAS) the uplink radio load on 1030 MHz could be estimated with a known number of ground interrogators. In contrast to this, an unknown number of non-selective responding transponders led to a drastic radio load increase on the downlink channel 1090 MHz.

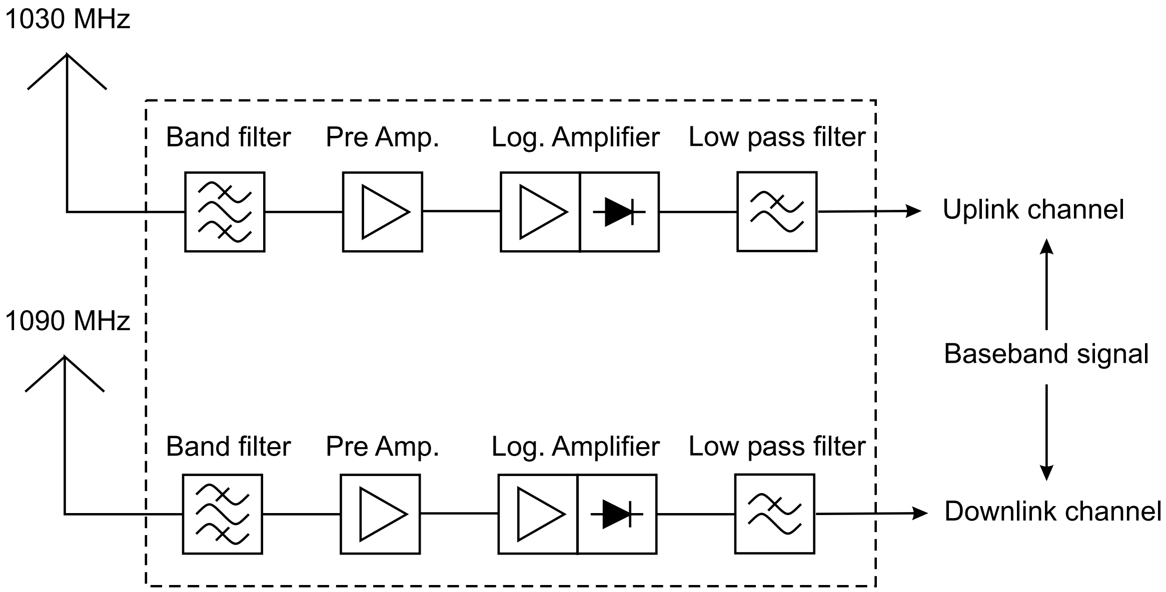


Figure 1: Receiver for both SSR channels

To make things even more difficult, the growing ACAS equipment extent of aircraft actually increases the traffic on 1030 MHz because ACAS instruments act like ground stations and interrogate on the common uplink channel.

In Germany like in most other countries there exists currently no flight inspection of radio load on the SSR channels. The following sections therefore describe an experimental system and new analyze methods to perform a selective investigation on both uplink and downlink channel.

## RECEPTION OF SSR SIGNALS

Transient, short pulsed signals with a high dynamic range require logarithmic receivers because a conventional automatic gain control (AGC) cannot quickly enough adapt the current signal strength.

Modern logarithmic amplifiers directly operate in the RF band with a low noise figure and due to their implicit rectification they deliver directly a baseband video signal. As shown in fig. 1 the expense to contruct a complete double channel receiver can be highly reduced applying those types of amplifiers. Preselecting the RF signal with a steep band pass filter and pre-amplifiying it enables to feed the log. amp. directly so we get the SSR video at the output. An analog-digital converter can be connected after the signal is fed through an anti-aliasing low pass filter and a further linear amplification.

## SIGNAL RECORDING

In order to investigate the effectiveness of different analyzing methods a continous recording of the video signal is required. The signal processing of raw data is done in *post processing* to test if the calculated solutions are reproducible.

The constant bandwidth of SSR signal contents is a contrast to the continously increasing speed of computers. The bandwidth of modern PC architectures allow a recording speed of 20 MByte/s or more without loss of data which corresponds to the selected 8 Bit wide A/D conversion at a sample rate of 20 MHz. The recording system is the one as introduced in [1] and bases on an CompactPCI platform with *LINUX* as its operating system. The author suggests to replace the old-fashioned method of recording and visualizing SSR video data with an oscilloscope and camera-based system described in [4, Att.A to App.F] by a modern variant as mentioned before.

In addition to the radar raw data the PC also records the real time-synchronized flight path data from the Flight Inspection System (FIS) with a repetition rate of 0.1 s.

## IN-FLIGHT MEASUREMENTS

According to former investigations of FAA and DFS [6] the air space above Frankfurt is regarded as the one with the highest radio load in the world on both uplink and downlink channel. During the ferry flight on 17-Sep-2001 to a regular flight inspection in Switzerland the Frankfurt/Main air space was passed by a few NM at 07:00 UTC. The crossing height was flight level 286 and both SSR channels were recorded for a few minutes as shown in the geographic scenario in fig. 2. The labeled moments are referenced to the beginning of the time synchronization with the FIS whilst the Airport Surveillace Radars (ASR) identify Frankfurt Airport and Götzenhain is the only radar in Germany with Mode S capability. To perform that test flight the experimental system was installed aboard of D–CFMB and connected to a bottom L-band antenna just as to the FIS.

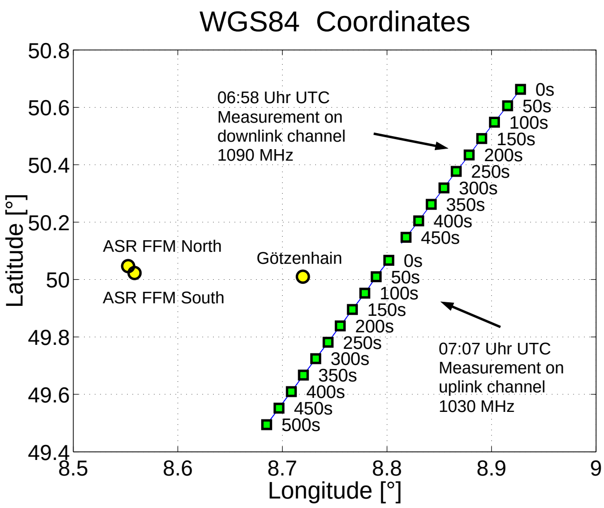


Figure 2: Flight path and moments of the measurements on 17-Sep-2001

## CORRELATION OF SSR TELEGRAMS

To separat the received SSR telegram formats in uplink and downlink one has to compare the recorded *Signal-in-Space* data with the known SSR telegram patterns. The relevant formats are shown in fig. 3 (refer to [2]).

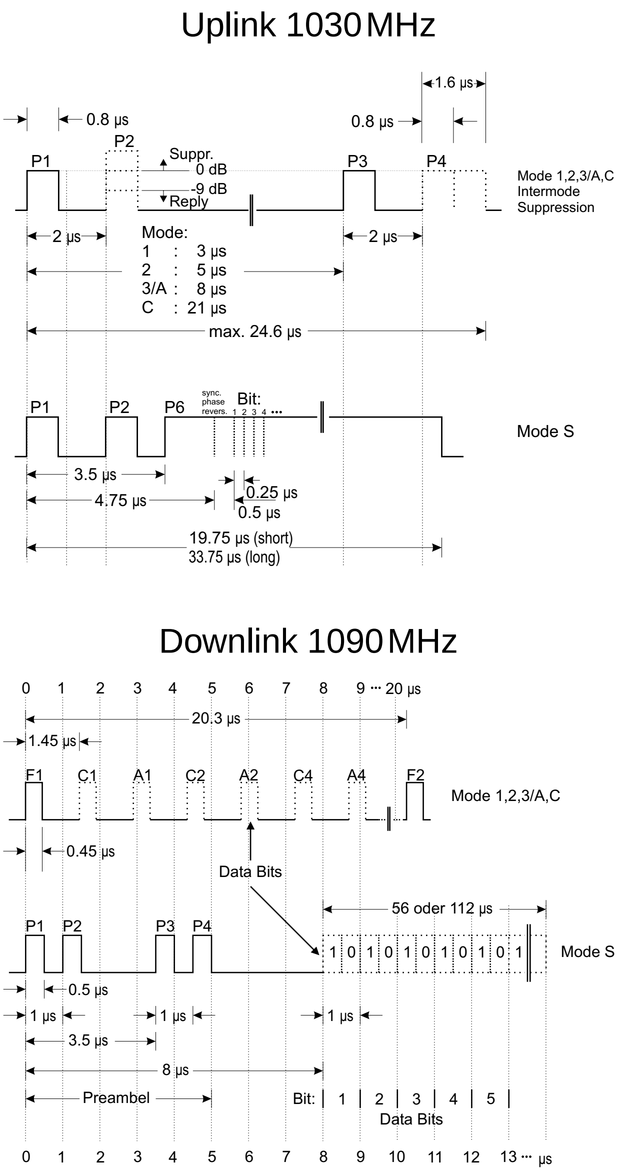


Figure 3: SSR telegram formats

The conventional uplink formats differ in their distance between P1 and P3 while the amplitude of pulse P2 indicates a side lobe transmission and prevents the transponder from replying. In case of Mode S there is a preambel consisting of P1 and P2 followed by the DPSK (Differential Phase Shift Keying)-coded data pulse P6. Mode S SLS (Side Lobe Suppression) is realized by a pulse P5 which jams the *Sync Phase Reversal* so the transponder does not react either. Furthermore, Mode S capable radars can add a following pulse P4 to the telegram which only triggers conventional transponders. This feature is especially used by ACAS which recognizes also conventionally equipped aircraft by transmitting *Whisper-Shout* sequences [2, *Att. A 3.1.2*].

The content of a reply to all conventional interrogations is surrounded by two frame pulses F1 and F2 within a constant interval whereas a Mode S reply is led by a 4 pulse preambel.

Generally the existence of those relevant pulses has to be checked in order to recognize a valid interrogation or reply. However, i.e. if many transponders reply in a highly overcrowded air space there may occur *Synchronous Garbling* so the radar signal procession cannot anymore detect single reply formats.

In contrast to this, the recorded video raw data of the experimental system allows to test and to optimize software algorithms which offer a better performance. A well-known method of pattern recognition is the discrete autocorrelation function (ACF) [5]:

$$\phi_{SS}(m) = \sum_{n=0}^{N-1} s(n)s(n+m)$$

It comprises a stepwise multiplication and summation of the SSR model sequence $s(n)$ with the raw data with a total length of $N$. In case of $m = N$ it reaches maxmimum compliance and therefore indicates a valid telegram at a clear time of arrival.

Selected correlation patterns $s(n)$ like the GPS *Gold Codes* cause steep maximums and a large main-to-side-lobe ratio but SSR telegrams are not trimmed to reach maximum correlation performance. Therefore it is necessary to include further security checks if a maximum is found.

The application of the ACF with SSR signals is illustrated in fig. 4. In the upper diagrams two recorded sequences are displayed: A military Mode 2 and a Mode S interrogation.

The model patterns below include different valuations during pulses and gaps which leads to a better maximum detection performance: Passing by single steps $n < N$ during its run the ACF reaches negative values if one or more recorded pulses are shifted into pattern gaps as shown in the lower diagrams whereas the main maximum is achieved if a total congruency of model pattern and recorded data is given. Due to the fact that a conventional Mode 2 interrogation may include a P2 in case of SLS the valuation within this pulse duration is set to zero in order not to falsify the ACF result. As a result of adapting different model pattern valuations it was possible to correlate telegram formats down to the receiver base noise level –90 dBm.

Things are getting more complicated if the downlink channel is concerned where it becomes clear that the evaluation of the ACF maximum cannot be the only criterion to be taken into consideration. Fig. 5 shows the corresponding diagrams of two downlink telegram formats. Within the Mode 1,2,3/A,C (left) reply frame pulse 4 octal numbers are encoded so $4 \cdot 3 = 12$ gaps or pulses are statistically distributed. The model pattern regards those positions as neutral and therefore its portions of the total ACF value are zero. Only the two frame pulses F1 and F2 effect a positive ACF value which leads to a fairly unusable main-to-side-lobe ratio comparing the results with the uplink channel. Consequently, another aspect must be the amplitude of the frame pulses at their known positions. The linear difference of their A/D converter values can be expressed in dB due to the calibration curve of the LogAmp so a logarithmic threshold is applicable.

Focussing on the Mode S downlink format (right) things are easy as on the uplink channel: A relatively long preambel preceding the information pulses causes a unique positive maximum without ambiguity.

Summing up those aspects we point out the following necessities to detect sucessfully SSR telegram formats applying the ACF algorithm:

- Maximum value of ACF as a mark of identification
- Signed valuation of model telegram patterns
- Ratio of significant pulse amplitudes

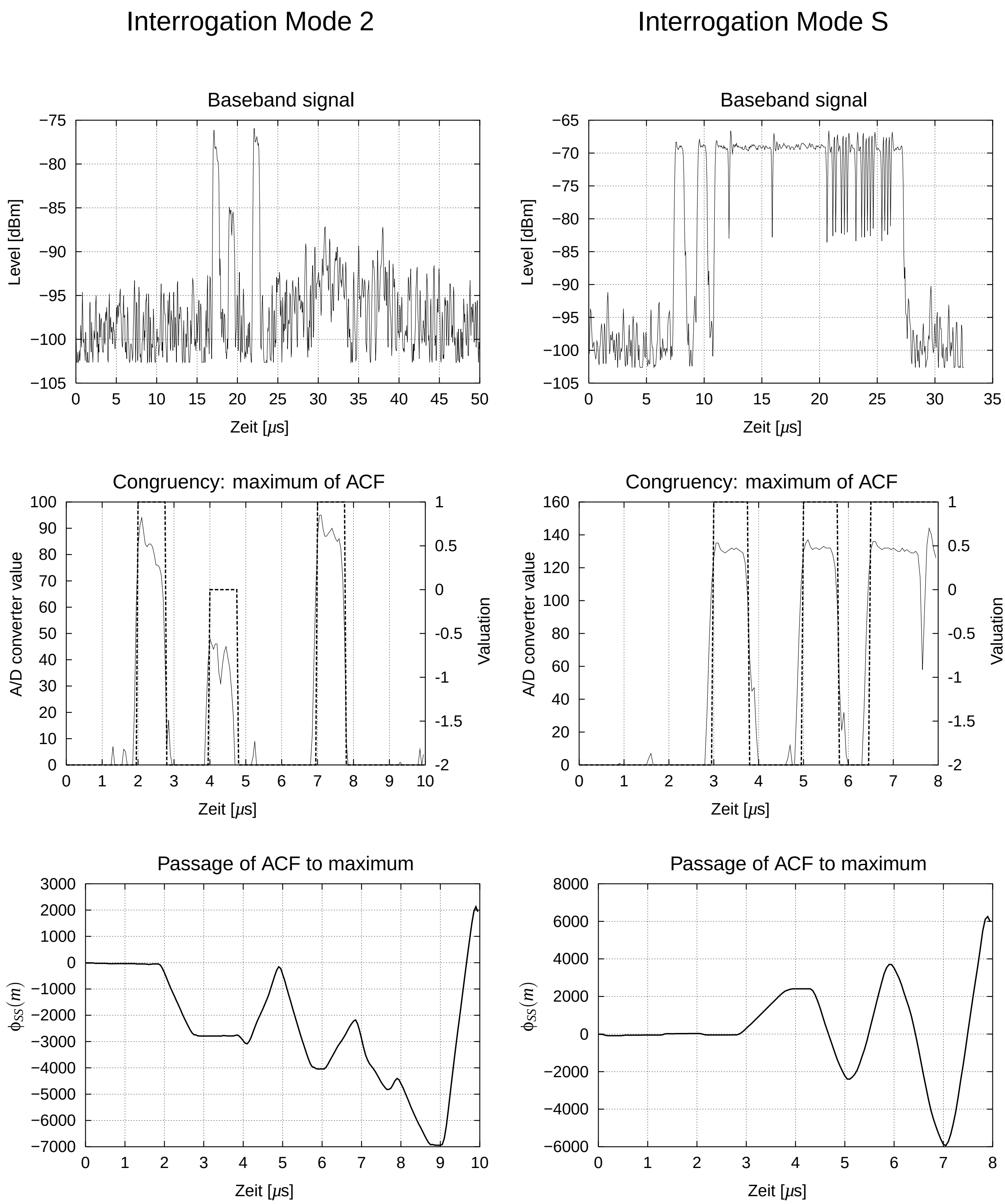


Figure 4: Autocorrelation function in the Uplink channel

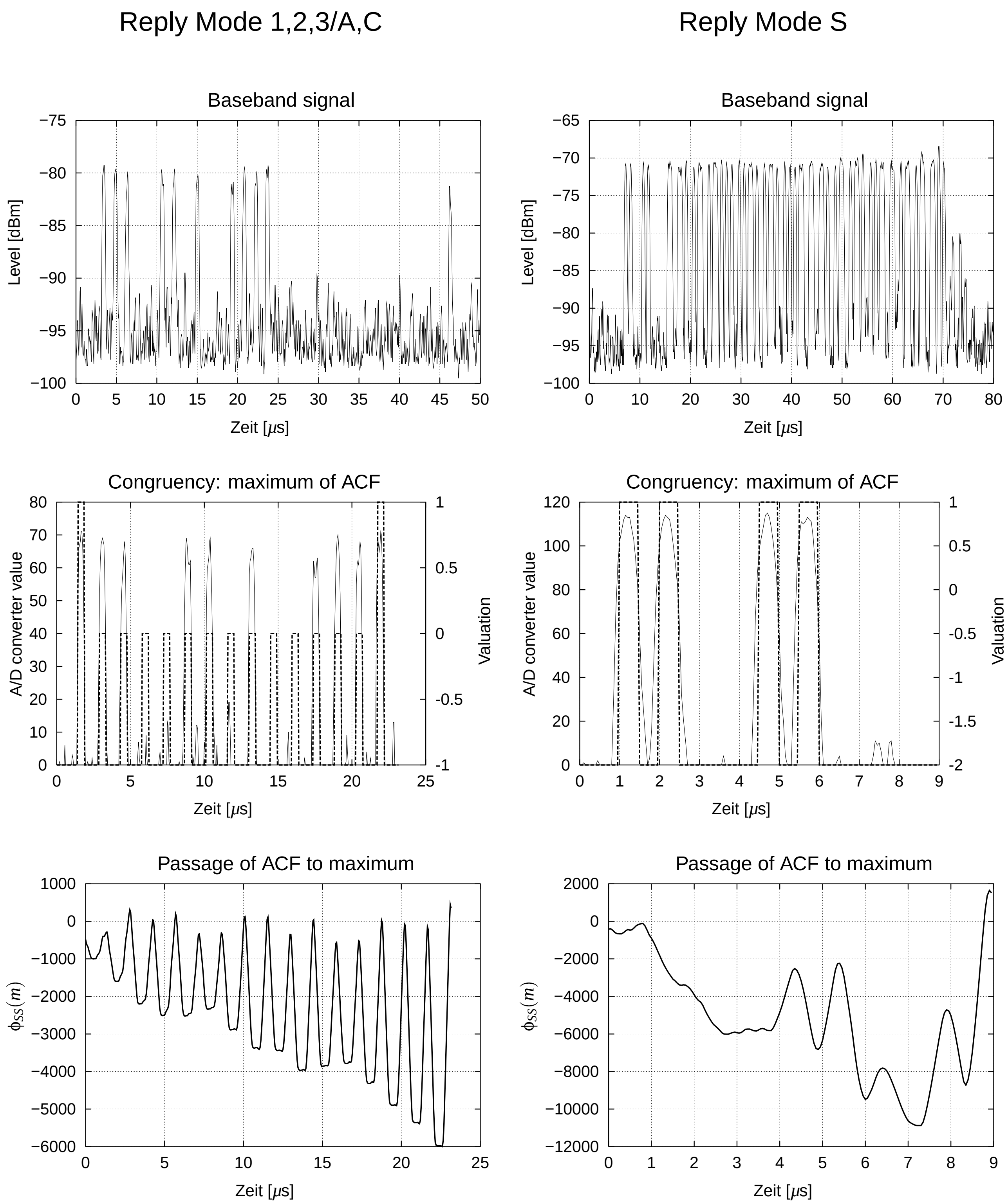


Figure 5: Autocorrelation function in the Downlink channel

PRESENTATION OF RADIO LOAD CALCULATIONS

By applying the decribed techniques it becomes possible to perform a refined analysis of the collected SSR raw data. Within the FIS time slot of 100 ms all telegrams are summed up and displayed over a time axis which corresponds to the flight path as depicted in fig. 2.

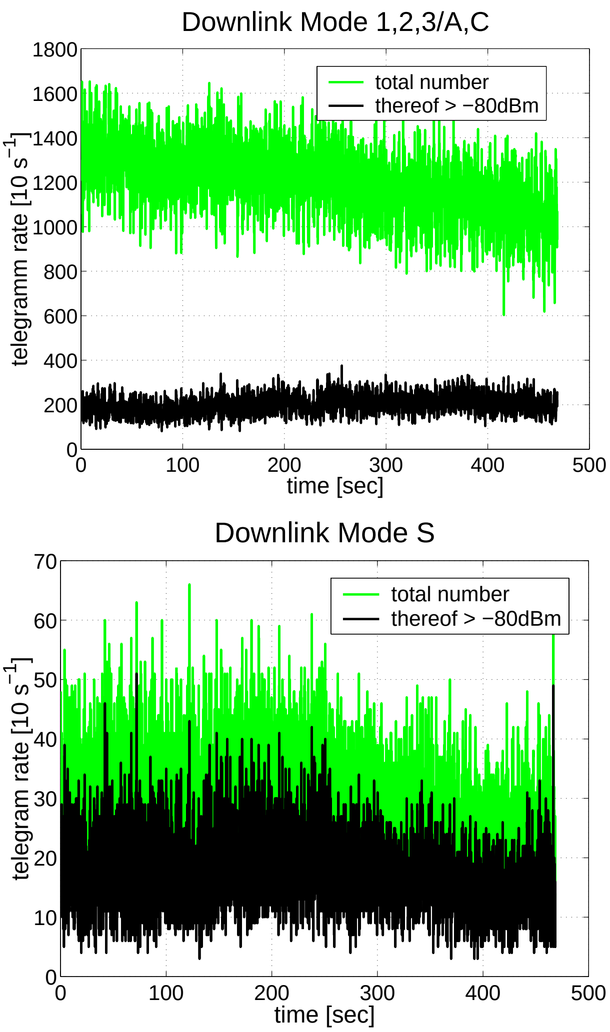


Figure 6: Downlink telegram rates

Evaluating the downlink channel first fig. 6 depicts the total number of correlated replies including all replies down to the limit of the receiver's sensitivity. More than 15000 conventional telegrams/s (above) statistically significate that every 67$\mu s$ a 21$\mu s$-lasting reply is received. Setting the minimum threshold up to –80 dBm on the contrary shows that most of the telegrams in space are fairly weak.

The number of Mode S replies (below) is ten times smaller than the conventional radio load. It mainly encloses the Mode S transponder *squitter* broadcasts and replies to ACAS interrogations of aircraft.

On the uplink channel 1030 MHz a more detailed subdivision of conventional modes can be achieved according to fig. 3.

The results of pure military Modes 1 and 2 are shown in fig. 7. In contrast to the total number of correlated interrogations those with a level above –77 dBm are separated (left) which corresponds to the minimum trigger level (MTL) of transponders according to [3, sec. 3.8.1.7.5.1]. Generally these evaluations concern real interrogations (P1$>$P2) whereas a distinction between main and side lobe interogations is possible by making full use of the SLS-indicator P2. The result (right) describes a high portion of interrogations received from the main lobe.

An expected higher activity can be determined in the squawk interrogation Mode 3/A and in the civil altitude interrogation Mode C rate as depicted in fig. 8. Mode A interrogation rates of civil radars are higher than Mode C and in addition with military Mode 3 the amount of 3/A is clearly higher than Mode C in general.

The preceding considerations did not include Intermode C interrogations elicited by ACAS Whisper-Shout acitivity. Nowadays more and more aircraft are equipped with ACAS which leads to the measured high interrogation rate as shown in the upper two diagrams in fig. 9: A large number of more or less far away ACAS-equipped aircraft transmit whisper-shout sequences whose initial transmissions are of weak output power. This explains the big difference between the total number of correlated telegrams and those above MTL. Comparing the two numbers above MTL one can derive that the activity of ACAS Intermode C and Mode C ground interrogation is mostly balanced.

In the lower diagram the Mode S interrogation rate is presented. Due to the fact that the Mode S extension of Götzenhain radar was disabled during the test flight the activity is traced back only to ACAS-equipped aircraft. Like before the majority of detected telegrams is below MTL what indicates a huge number of aircraft flying at a large distance.

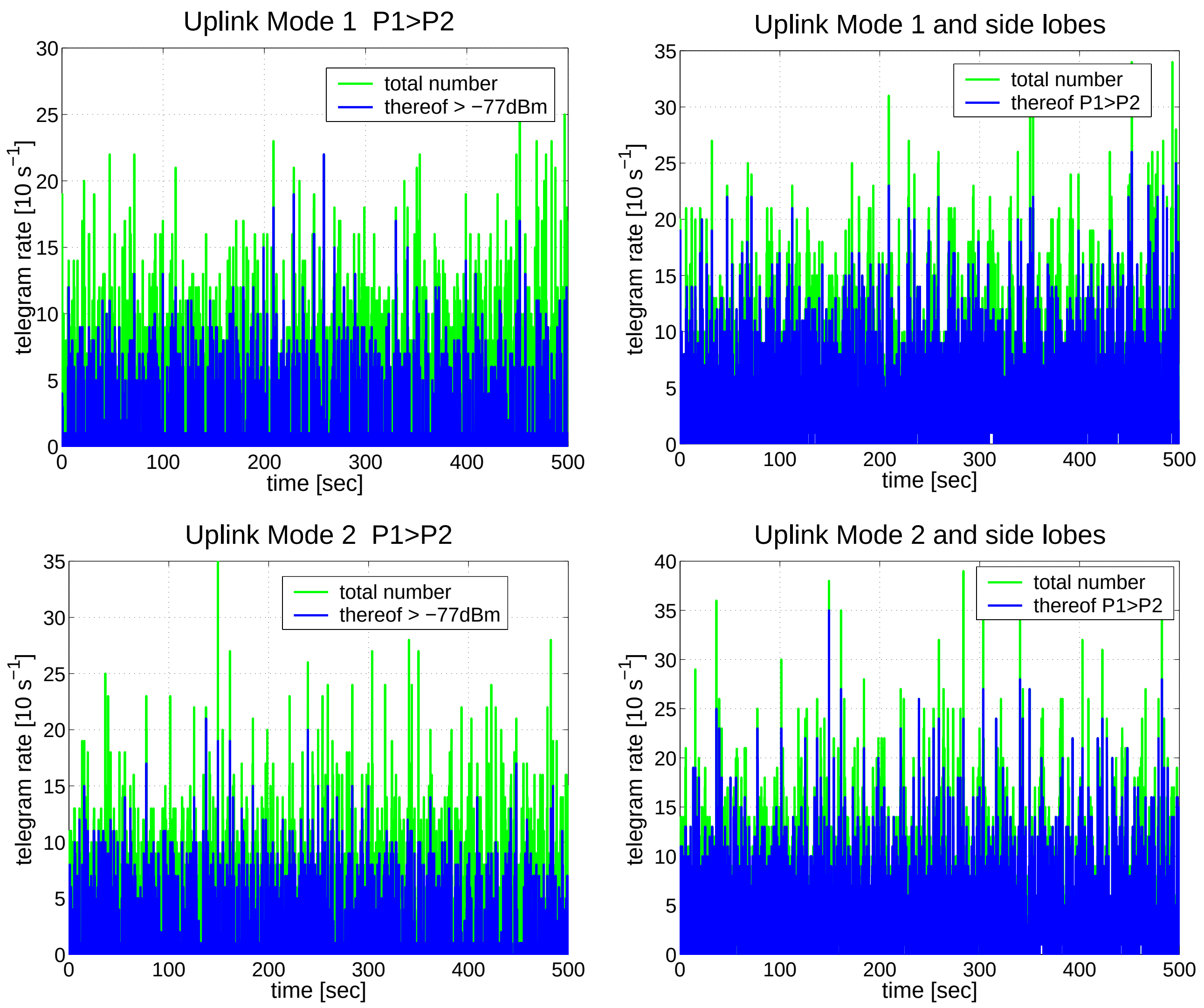


Figure 7: Military interrogations

The composition of both Intermode C and Mode S radio load is higher than the combined interrogation rate of civil SSR radars. As a result of this, the uplink channel is affected more and more by the increasing equipage grade of ACAS. On the uplink channel one cannot distinguish between military, civil ground station or ACAS-elicited replies so a definite statement about the influence of ACAS is not derivable.

## CONCLUSIONS

An experimental system capable of receiving and recording SSR signal-in-space as video raw data was introduced in this paper. In context with the described algorithms to detect different uplink and downlink telegrams formats it is now possible to evaluate the SSR radio field load .

Currently all calculations are processed after the recordings are finished. Within the first steps to establish its usage as a *radio field monitor* it is necessary to investigate various methods and algorithms to improve their performance with respect to a high detection security. The main aspect is to get reproducable results that are based on proper scientific methods.

In order to generate instant results it is necessary to implement tested and approved software algorithms as hardware. Due to the fact that all operations deal with integer values the implementation could be realized with highly integrated *Complex Programmable Logic Devices* (CPLDs). The technical conditions can be taken for granted nowadays.

The integration of a mobile radio field monitor into

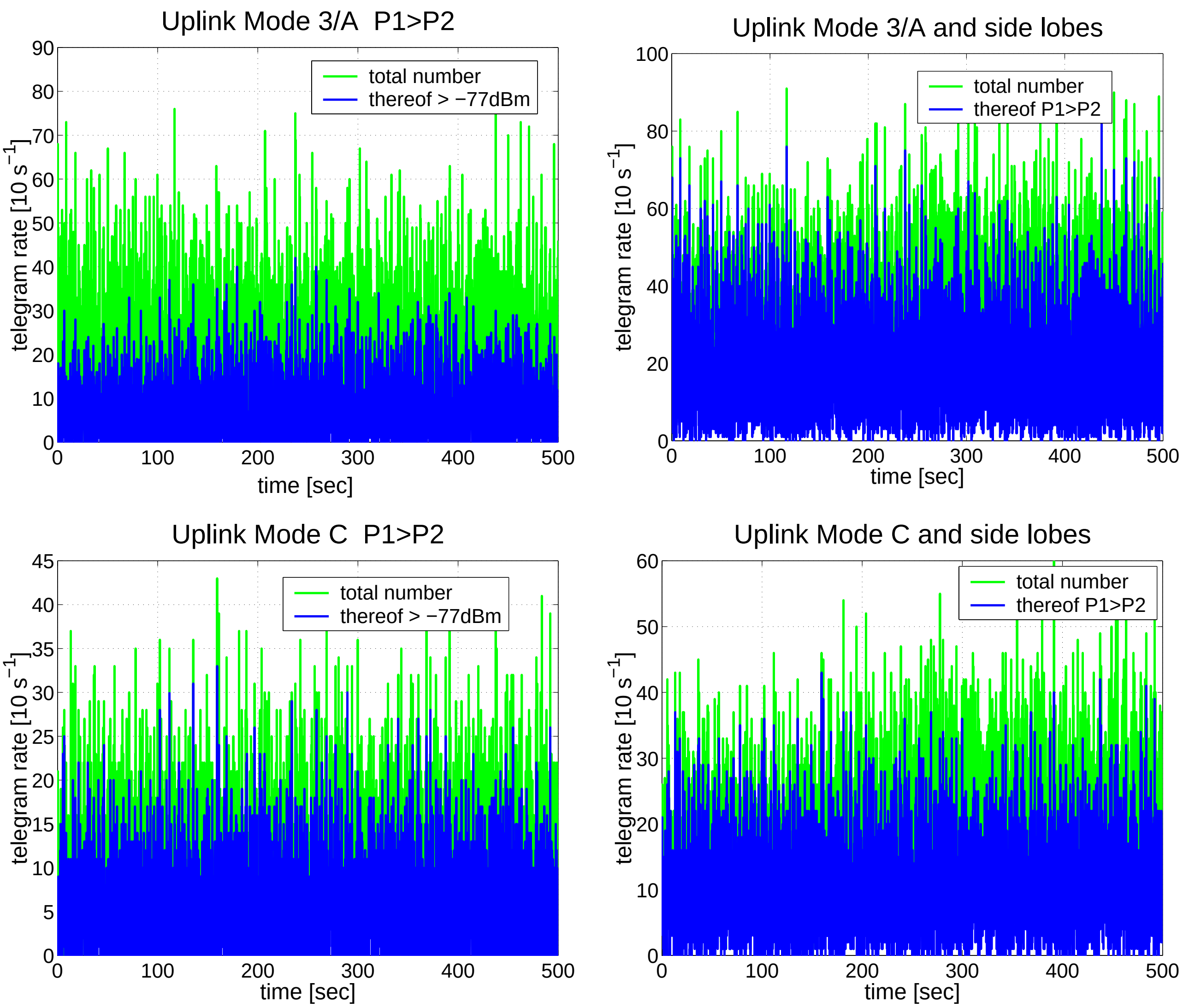


Figure 8: Mode 3/A and C interrogations

flight inspection procedures comprises the potential to get an overview of the current radio field load. Especially in critical air spaces a cyclic SSR flight inspection would provide a differentiated analysis of the current status and may early detect the reason for a reduced reachability of aircraft transponders by SSR ground stations due to garbling effects. Furthermore, the analysis of recorded video data could also reveal jamming signals which possibly block transponders and may help to locate the disturbance source. The system's main benefit is therefore the effective assistance of maintaining the backbone of ATC.

## ABBREVIATIONS

| | |
|---|---|
| ACAS | Airborne Collision Avoiding System |
| ACF | Autocorrelation Function |
| A/D | Analog to Digital (Conversion) |
| AGC | Automatic Gain Control |
| ASR | Airport Surveillance Radars |
| ATC | Air Traffic Control |
| CPLD | Complex Programmable Logic Device |
| DFS | Deutsche Flugsicherung GmbH |
| DPSK | Differential Phase Shift Keying |
| FAA | Federal Aviation Administration |
| FIS | Flight Inspection System |
| GPS | Global Positioning System |
| IFF | Identification Friend or Foe |
| MTL | Minimum Trigger Level |
| SLS | Side Lobe Suppression |
| SSR | Secondary Surveillance Radar |

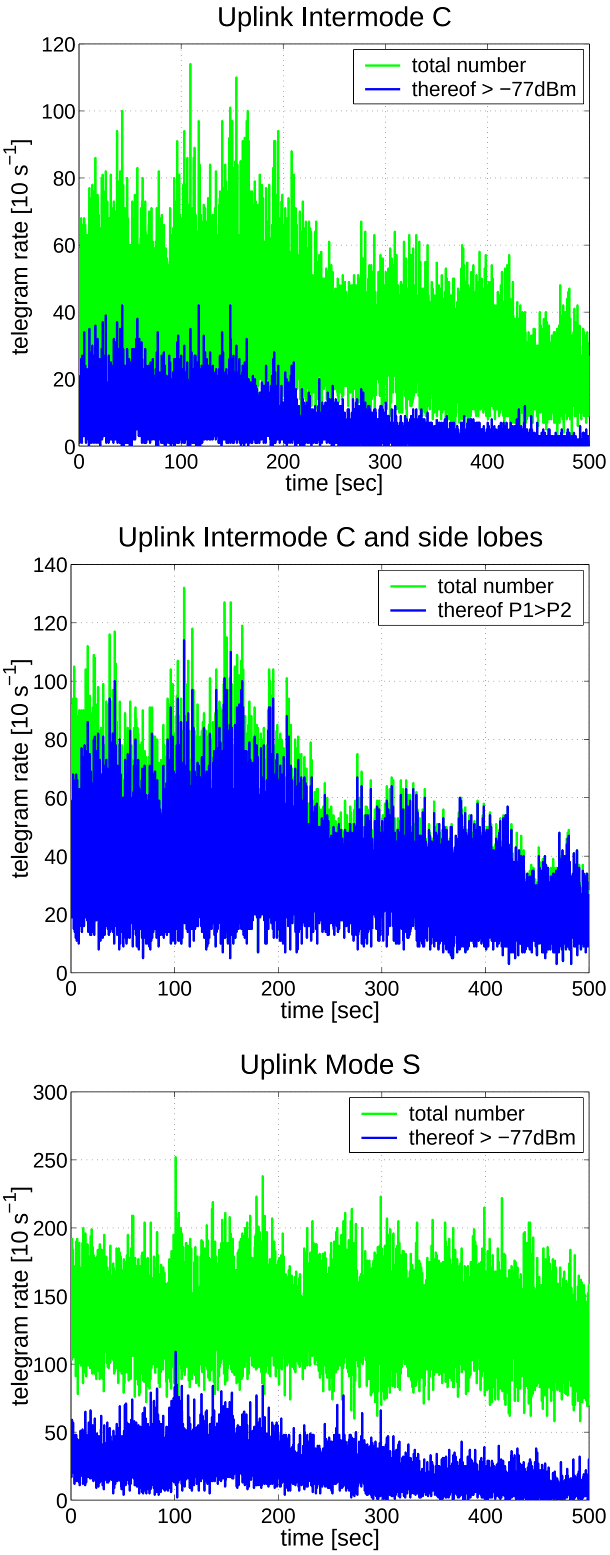


Figure 9: Intermode C and Mode S interrogations

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